Using sensor systems and standard project models to capture and model project history for building commissioning and facility management

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1. Background

Advances in sensor and tagging systems provide a way to capture the as-built history of a construction project to be utilized during facilities management. Recent developments in generating 3D environments using laser scanning technologies, and in acquiring quality information about built environments using embedded and other advanced sensors create an opportunity to explore the feasibility of frequently gathering complete and accurate three-dimensional and quality-related as-built data frequently throughout the construction and facility management phases of a facility [Akinci et al 2002a; Gordon et al 2003].

Similarly, advances in Radio Frequency Identification (RFID) technology minimize earlier technological problems, such as metal interference, and economical limitations and can be applied to provide an environment to capture, store and communicate data in addition to the ID information on the component [FIATECH 2003; Akinci et al 2002b]. As a result, it is now possible to deploy this technology to capture the history of various facility components throughout the facility lifecycle and hence enable components to achieve Level 1 intelligence, which is defined as having a unique identification, being capable of communicating its status (form, composition, location, key features) effectively with its environment, and being capable of storing data about itself (current and historical data) [EPCGlobal 2003].

The current trends in the A/E/C industry for the use of integrated project models have also shown that a semantically rich integrated project database, combining multiple views for project participants, can support various project management and facility management functions [e.g. Froese et al 1999; Yu et al 1998]. These standard models provide an opportunity to support data exchange during building commissioning, which is an activity that occurs at the interfaces between different phases of a facility delivery life cycle.

This paper discusses three on-going research projects at Carnegie Mellon, focusing on utilizing different sensor systems and RFID technologies to capture the history of a facility and assessing the capabilities of Industry Foundation Classes for enabling the data transfer during building commissioning.

2. Problem Statement

Not having a complete project history of as-built conditions of facility components results in a waste of time and money during operation and maintenance of a facility. Not capturing and storing a complete project history minimizes the learning that can occur within an owner organization.

In addition, when a problem occurs with a component during facility management, one might need to access the history of a component to correctly diagnose and resolve the problem effectively [Akinci et al 2002b]. For example, when a crack occurs on a precast component, to be able to correctly diagnose the problem, one needs to access information about material, casting and curing processes during the manufacturing phase, the transportation and installation conditions from the construction phase, and any special conditions that the component might have faced during its service life [Akinci et al 2002b; Ergen et al 2003]. Currently, most of these information items are stored in various documents and memos, while some are stored digitally in distributed databases located in several companies. As a result, it becomes very difficult to collect all the historical information needed to correctly diagnose and resolve the problem, and a significant amount of time and money can be wasted to resolve the problem. This issue is further pronounced on components such as pipe spools and HVAC ducts that need to be continuously maintained throughout facility operations and maintenance.

Finally, data collected during building commissioning, which occurs multiple times from the design until decommissioning of a facility, is currently stored in reports. Building commissioning provides important information that can be utilized during facilities management. It is beneficial to leverage current standardization efforts, such as Industry Foundation Classes, to transfer the data captured and stored in building commissioning systems to different facility management systems. The latest version of the Industry Foundation classes provide some specifications that can be utilized for capturing and transferring building commissioning data. However, further specifications need to be developed to be able to fully support that process.

3. Approaches, Examples and Results

This section describes three on-going research projects at Carnegie Mellon that leverage the technologies described in Section 1 and focuses on addressing the problems stated in Section 2.

3.1. Capturing the history of a construction project using laser scanners, embedded sensor systems and integrated project models

In this research project, we target not only capturing the history of a construction project, but also analyzing the data captured and identifying possible non-conformances at the time that data is collected. A large percentage of non-conformances in construction occur during the construction process, resulting in costly rework and adversely affecting the overall performance of the built environment [e.g., Burati and Farrington 1987]. Researchers from the Architecture, Robotics, and Civil and Environmental Engineering departments at Carnegie Mellon University are exploring the utilization of reality capture technologies, and data modelling approaches for identifying non-conformances early in the construction process and for capturing and storing the history of a construction project [Akinci et al 2002a; Gordon et al 2003].

In our approach, we use a core "living" (continuously updated and maintained) project model composed of a three-dimensional design model with explicit design specifications and multiple views, a construction process model, and an as-built model of a facility to store the history of a facility. The product model and the construction process models are obtained from design and scheduling software systems. Using this information, we create inspection plans for scanning and embedded sensing to be utilized during construction. During construction, laser scanners and embedded systems are utilized to capture the as-built conditions and to provide frequent and accurate 3D geometric and quality-related (e.g., component identity, thermal, etc.) as-built information to the integrated project model. This project model provides the necessary project history for the project managers and owners of the facility. In addition, the defect detection and management modules in the proposed approach utilize this project model to identify critical spatio-temporal and quality-related deviations of the work-in-place and construction activities and products that are impacted from these critical deviations. It is expected that this defect management process will in turn trigger a change in the design and or in the construction schedule.

As part of this effort, we conducted several case studies on construction projects in Pennsylvania to identify challenges and opportunities in applying specific reality capture technologies and in coordinating suites of these tools on construction sites. During these case studies, we embedded sensing in concrete and frequently obtained laser scans. Below include some of the initial results obtained from these case studies [Gordon et al 2003].

3.1.1 Creating Inspection Plans and Determining Measurement Goals

It is inefficient to fully saturate a built-environment with embedded sensors and laser scanning activities. It is important to identify ahead of time what types of sensors should be utilized when. In the case studies, we reviewed available design documentation for requirements to be verified using laser scanners and embedded sensing at specific points in the construction schedule [Gordon et al 2003].

3.1.2 Embedded Sensing and Sensor Planning

Embedding sensors into a facility requires commitment to a certain location and time period for sensing, without the option to revisit the sensors for maintenance or replacement. Many issues, such as modality, location, time and duration of sensing, and data communication and storage, should be considered in an embedded sensor plan.

Sensor planning becomes much more difficult for larger deployments under the dynamic and complex conditions experienced on construction sites over time.

Given a construction schedule, design model, and defined inspection goals, the output of the embedded sensor planning process is a series of decisions of when and where to sense what properties of a component for how long and with what sensor. To simplify this process for the case studies, we used a single type of sensor and fixed a receiver and data logger in a secure construction trailer. In these studies, we discovered that the data logger needed additional memory to make sufficient temperature readings in the field, where the timing of concrete placement is more variable than under controlled conditions.

3.1.3 Laser scanner planning

The goal of laser scanner planning is to optimize the use of scanners to achieve a given set of measurement goals in the built environment. Total saturation of the construction environment with laser scans is an inefficient option and at the same time, sparse scanning risks missing areas of interest that may be occluded or otherwise hard to access for necessary measurements. To minimize the cost of scanning, researchers from the Robotics Institute are constructing an algorithm that determines optimal scanner configurations based on current site conditions, measurement goals, and the goal of minimizing costs. The algorithm developed so far performed well on the case study site with few overlapping goal spaces, but had difficulty when multiple goals existed in close proximity.

3.1.4 Laser scanning

Given laser scan plans, we experimented with two laser scanners : (1) a commercially-available Zoller + Fröhlich LARA 25200 (Z+F scanner), (2) a research test-bed, composed of two actuated SICK lasers (CTA scanner). The Z+F scanner is able to scan 360° horizontally and 70° vertically, and capture range and reflectance data for each point. It has a maximum range of 25 meters. It takes approximately 90 seconds to complete a scan. We averaged 6 minutes per scan with spin-up time and interface navigation included. Figure 1 shows an example of that scan. The CTA scanner is made of two SICK lasers: one mounted horizontally and one vertically, with each able to scan a 180° line. The CTA scanner has a maximum range of 80 meters. A scan takes approximately 45 seconds to complete; total scan time, including spin-up time and interface navigation, averages 2 minutes.

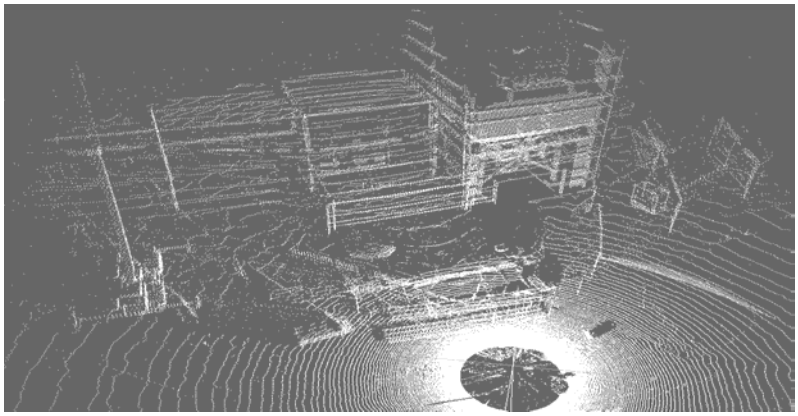

Figure 1. Z+F scanner output (from Gordon et al 2003)

The scale and detail required for each measurement goal determines the choice of scanner. Data generated from the Z+F was of very high density and quality, with one problem: range data that exceeds 25 meters wraps around to 2 meters. We found that the ability to scan up to 80 meters, as in the case of CTA scanner, can make construction applications of laser scanning time-effective, especially for a large number of measurement goals [Gordon et al 2003].

3.1.5 Object Recognition

Using the 3D point cloud output of the laser scanning process, the team was able to visualize the geometric as-built site conditions. However, a point cloud does not provide an optimal representation to allow high-level reasoning about defects and their early detection. In addition, the goal of capturing the history of a project can be achieved by recognizing and representing objects in a scene. Object recognition provides the bridge between the raw data and a CAD model of the site, abstracting the point cloud data into a higher-level, more portable representation. The algorithm developed by the team can detect objects with arbitrary and unknown pose. The existing site model provides an initial estimate of the location of the model objects within the 3D point cloud. This a priori knowledge allowed us to focus the recognition algorithm on the relevant region of the data and to process the data at a higher resolution than would be possible if the entire point cloud was used.

3.1.6 Representation of as-built information in standard project models

To automate the assessment of as-built conditions and to be able to represent and store the history of a construction project, both as-built and as-designed models need to be represented in a semantically rich way and the necessary relationships between these two models need to be created and maintained throughout construction. IFC Rel 2x. specifications have limitations in modeling as-designed and as-built information into one project model to support the automation of as-built conditions. It is necessary to extend the current IFC representation without increasing the complexity unnecessarily from both an understandability and a processability point of view. For the purpose of allowing IFCs to represent both design and as-built information in one project model simultaneously, we propose a solution that allows for fast processing of the IFC model without increasing the complexity of the IFCs. This was accomplished through the utilization of the *IfcRepresentationContext* concept in IFCs and adding a new attribute called Context to the *IfcRelationship* class.

3.2. Utilizing RFID tags to capture the history of a component

RFID is an automatic identification technology used to identify, track, and detect various objects. RFID systems are composed of two components: a tag, and a reader. An RFID tag is an electronic label that stores data and is attached to objects. Readers, which send RF (Radio Frequency) signals for communication, are used to read data from these tags. A reader is composed of an antenna, a transmitter/receiver and decoder. Current RFID technologies use three frequency ranges: low (100-500 kHz), intermediate (10-15 Mhz), and high (850-950 Mhz / 2.4-5.8 Ghz). RFID tags can be classified as either active or passive based on the power source. An active tag has an internal battery for power. A passive tag utilizes the energy generated by a reader/antenna. Active tags have a greater read/write range (up to 30 m). However, they are larger in size, more expensive, and have a limited life span (5-10 years). Passive tags are cheaper, smaller, lighter, and have unlimited life span. However, they require a more powerful reader and have shorter read ranges. Tags also can be read only (RO), read / write (R/W) or write once / read many (WORM). After the data is read from any type of transponder, it can be sent to a host computer, or stored on a reader to be later uploaded to a computer [Akinci et al 2002].

In this research, we leverage these features of the RFID technology and assess the capability of this technology to store some critical historical information about a component so that various related parties can access and write relevant information as the component moves through its supply-chain.

We are currently performing several pilot case studies in a precast manufacturing and a pipe spool manufacturing plants. The initial results of a field test done at a pipe spool manufacturing plant showed that active tags operating at 433.92 MHz frequency at a read/write distance of 60-150 feet work well for storing some information on the tag and reading id and other information from multiple tags in a short period of time [FIATECH 2004].

3.3. Evaluation of IFC specifications to support building commissioning

ASHRAE defines commissioning as the process of ensuring that systems are designed, installed, functionally tested and capable of being operated and maintained to perform in conformity with the design intent (Guideline 1-1996). The role of commissioning, as we call it embedded commissioning, is to complement each of the lifecycle phases and their interactions through timely building system evaluation. To be able to support this, current standardization efforts, such as Industry Foundation Classes, need to represent the building commissioning data to be exchanged at different phases.

Our approach includes developing a prototype system to collect building commissioning information and a test rig to assess the capabilities of various releases of Industry Foundation Classes in exchanging the necessary building commissioning data (Figure 2). We approach this from two angles. First, we are exploring the representational needs of building commissioning process and the management of building commissioning data. The second facet of our approach is testing the adequacy of Industry Foundation Classes for support of commissioning process and exploring the possibilities of data exchange.

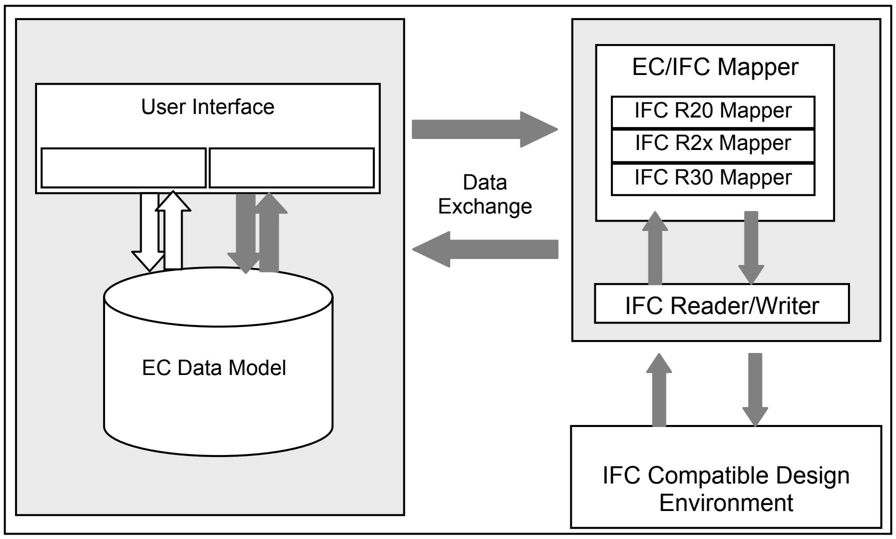

Figure 2. Building Commissioning based IFC Test Rig

Initially, we have focused our effort developing a representation schema that shows the data that need to be represented for building commissioning activity performed for HVAC components during post-construction. We specifically focused on developing data models for fans and air filter units. We have tried mapping our building commissioning fan and air filter model to IFC release 2. In that case, we were able to represent about 60% of the building commissioning data items using IFCs. In the recent release of IFCs, the data representation within the HVAC domain got significantly augmented with the use of predefined property sets. Using that release, we were able to map 90 % of our information to the specifications. We are currently performing further tests and developing and testing additional data models within the HVAC domain.

4. Conclusions and Recommendations

Reality-capture technologies, such as laser scanners and embedded sensing systems, available to the Architecture/Engineering/Construction industry provide a way to capture the history of a project to be used during facility management. Similarly, advances in RFID technologies enable the capture and storage of a product's history on the product itself and enable Level 1 intelligence for facility components. To be able to get full benefits from these technologies, it is necessary to plan for how these technologies can be utilized on construction sites. In addition, data modeled in current standard project models, such as Industry Foundation Classes, should be enhanced to enable the representation of the data captured in these devices. Finally, additional specifications also need to be developed to enable embedded commissioning, which complements each of the lifecycle phases and their interactions through timely building system evaluation.

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